

## MgB<sub>2</sub> SUPERCONDUCTORS

This application claims the benefit of U.S. Provisional Application No. 60/275,067, filed on March 12, 2001.

### BACKGROUND

#### Field of the Invention

This invention relates to superconductors and devices based on superconductors.

#### 5 Discussion of the Related Art

Recently, Akitmitsu et al. discovered that a well-known compound, i.e., MgB<sub>2</sub>, exhibits superconductivity at temperatures lower than about 39 Kelvin (K). Powders formed of MgB<sub>2</sub> are produced by chemically reacting magnesium (Mg) and boron (B) at a temperature in the range of about 800° Celsius to about 950° Celsius (C). Powders of polycrystalline MgB<sub>2</sub> in which individual crystalline grains of MgB<sub>2</sub> have diameters in the range of about 1 micron to about 50 microns are available commercially.

### SUMMARY

In one aspect, the invention features a solid structure. The structure includes a substrate and a layer located on a surface of the substrate. The layer includes crystalline or polycrystalline MgB<sub>2</sub>.

In another aspect, the invention features a process for making a thin-layer device. The process includes providing a solid body of MgB<sub>2</sub> and ejecting MgB<sub>2</sub> from the body by directing laser light onto the body. The process also includes growing a layer on a surface of a substrate from a portion of the ejected MgB<sub>2</sub>.

### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a magnified view of a portion of a solid polycrystalline body formed of MgB<sub>2</sub>;

25 Figure 2 is a flow chart for a process of producing the body of Figure 1;

Figure 3 shows a structure that includes a thin layer of MgB<sub>2</sub>;

Figure 4 shows a setup for producing the thin-layer structure of Figure 3 by pulsed laser deposition (PLD);

Figure 5 is a flow chart for a process for making the structure of Figure 3;

Figure 6 shows a superconducting quantum interference device (SQUID) formed from the thin-layer structure of Figure 3; and

Figure 7 shows a helium level gauge that uses the body of Figure 1.

### DETAILED DESCRIPTION OF THE EMBODIMENTS

Though recent discoveries have shown that  $\text{MgB}_2$  is a superconductor. The available powder form of  $\text{MgB}_2$  is not useful for many types of superconducting devices. Furthermore, the powder form of  $\text{MgB}_2$  is not adapted to use in many manufacturing processes. For these superconducting devices and manufacturing processes, solid bodies and thin layers of  $\text{MgB}_2$  are more convenient. Solid bodies and thin layers of  $\text{MgB}_2$  are provided by processes of various embodiments.

Figure 1 shows a portion of a three-dimensional solid body 10 of  $\text{MgB}_2$  having at least one linear dimension of 1 millimeter (mm) or more. The body 10 includes a plurality of crystalline grains 12-14 and is thus, polycrystalline. The grains 12-14 have diameters in the range of about 1 micron to about 50 microns. The solid body 10 is a superconductor, at least, for temperatures below about 39 K.

Figure 2 is a flow chart for a sintering process 20 that produces a solid body of  $\text{MgB}_2$ , e.g., the polycrystalline body 10 of Figure 1. The process 20 includes compressing a quantity of  $\text{MgB}_2$  powder with a pressure in the range of about 100 bars to about 50,000 bars (step 22). While being compressed, the quantity of powder is sintered at a temperature of about  $500^\circ\text{C}$  to about  $900^\circ\text{C}$  (step 24). In an exemplary embodiment, a pressure of about 20,000 bars and a temperature of about  $700^\circ\text{C}$  are applied to the quantity of  $\text{MgB}_2$  powder for time in the range of about 0.5 hours to about 2.0 hours. After the sintering, the process 20 includes gradually cooling the sintered  $\text{MgB}_2$  body to room temperature (step 26). The final sintered body is a polycrystalline solid adapted for use in superconducting devices and in extreme manufacturing processes such as pulsed laser deposition.

Figure 3 shows a thin-layer structure 30 that includes a  $\text{MgB}_2$  layer 32 and a substrate 34 on which the layer 32 is grown. The  $\text{MgB}_2$  layer 32 is polycrystalline or crystalline and has a thickness "d" in the range of about 10 nanometers (nm) to about 1 micron. The  $\text{MgB}_2$  layer 32 is superconducting at low temperatures, e.g., temperatures below about 39 K.

$\text{MgB}_2$  layer 32 and substrate 34 have similar lattice constants. In the plane of common surface 36, the lattice constants of the layer 32 and substrate 34 differ by less than 10 percent. In many embodiments, in-planar lattice constants differ by less than about 1 percent. The similarity of the in-plane lattice constants of the  $\text{MgB}_2$  layer 32 and the substrate 34 enables the  $\text{MgB}_2$  layer 32 to be grown in crystalline or polycrystalline form on the surface 36 of the substrate 34, because the similarity of in-plane lattice constants reduces strain energies during layer growth.

An exemplary substrate 34 is 6H-SiC (6-layer hexagonal silicon carbide), which has in-plane lattice constants of about 0.3081 nm along surface 36. These in-plane lattice constants are very similar to those of  $\text{MgB}_2$ . The lattice constants along surface 36 for the grown  $\text{MgB}_2$  layer 32 are equal to about 0.3085 nm.

Other exemplary substrates 34 include crystalline or polycrystalline solids formed of cubic SiC,  $\text{LaAlO}_3$ ,  $\text{SrTiO}_3$ , or sapphire. Since the substrate 34 is crystalline or polycrystalline and has in-plane lattice constants that closely match those of  $\text{MgB}_2$ , layer 32 is able to grow epitaxially or c-axis oriented on surface 36 of the substrate 34.

Figure 4 shows a setup 40 for producing the structure 30 of Figure 3 by pulsed laser deposition (PLD). The setup 40 includes a pulsed ultraviolet (UV) laser 41, a vacuum chamber 42, a target pellet 43, a crystalline substrate 44. An exemplary pulsed UV laser 41 has a wavelength of about 250 nm, a pulse rate of about 0.5 – 10 Hz, and an energy density on the target of about 1 - 50 Joules/cm<sup>2</sup>. The target pellet 43 is solid body formed of polycrystalline  $\text{MgB}_2$ , e.g., a solid body made by sintering process 20 of Figure 2. The substrate 44 is an epitaxial growth base for  $\text{MgB}_2$  such as a crystalline or polycrystalline solid of 6H-SiC, cubic SiC,  $\text{LaAlO}_3$ ,  $\text{SrTiO}_3$ , or sapphire. The substrate 44 is positioned to face the surface of the target pellet 43 that is struck by an output beam 46 of the laser 41. For example, the substrate 44 may be held vertically above the target

pellet 43 at a position that intersects a plume 52 of particles that is ejected from the target pellet 43 by the action of the pulsed laser beam 46 during PLD.

Figure 5 is a flow chart showing a PLD process 60 for growing a layer 45 of  $\text{MgB}_2$  with setup 40 of Figure 4. The process 40 includes providing a solid target pellet 43 of polycrystalline  $\text{MgB}_2$ , e.g., a pellet produced by sintering process 20 of Figure 2 (step 62). The process 40 also includes directing a pulsed output beam 46 from laser 41 onto the solid target pellet 43 (step 64). The pulsed output beam 46 ejects  $\text{MgB}_2$  particles 48-50 to form a plume 52 over the target pellet 43. The ejected particles 48-50 typically have diameters of about 0.1 nm to about 10 nm. A portion of the ejected particles 48-50 in the plume 52 are deposited on substrate 44 (step 66). The deposition produces an epitaxial growth of layer 45 of cubic  $\text{MgB}_2$  provided that the substrate 44 has in-plane lattice constants that approximately match those of  $\text{MgB}_2$  along the exposed surface of the substrate 44. For example, a mismatch of in-plane lattice constants by 1 percent still enables layer 45 to grow in a crystalline or polycrystalline form.

To improve the deposition of  $\text{MgB}_2$ , the substrate 44 and pellet 43 are positioned in a vacuum chamber 42, which maintains internal pressures in the range of about  $10^{-8}$  Torr to about  $10^{-4}$  Torr. Pressures in this range reduce oxidation of the  $\text{MgB}_2$ , which could produce  $\text{MgO}$ . The presence of  $\text{MgO}$  could otherwise interfere with the deposition of  $\text{MgB}_2$ . However, the inclusion of a small amount of  $\text{MgO}$  into the  $\text{MgB}_2$  layer could enhance certain superconducting properties such as the value of the critical current.

Figure 5 is an oblique view of a superconducting quantum interference device (SQUID) 70. The SQUID 70 is formed by etching thin-layer structure 30 of Figure 3, e.g., by a lithographic process, to remove the  $\text{MgB}_2$  from both central region 72 and tunneling junction regions 74, 76. After the etch, the structure includes a ring 78 of  $\text{MgB}_2$  whose current properties can be used to measure the value of the magnetic flux through the central region 72.

Figure 6 shows a liquid helium (He) gauge 80 that measures the height of the surface 82 of the He liquid 83 in dewar 84. The gauge includes an elongated body 86 of solid  $\text{MgB}_2$ , which is formed by sintering process 20 of Figure 2. The body 86 includes a cooler portion 88, i.e., located in the He liquid 83, and a warmer portion 90, i.e., located above the He liquid 83. The cooler portion 88 is superconducting, and the warmer

portion 90 is not superconducting. The gauge 80 determines the level of the surface 82 from the reading from an ohmmeter 92. Changes in the reading are proportional to level changes of the liquid He, because the resistance of the body 86 of solid  $\text{MgB}_2$  is proportional to the length of the body 86 that is not in the He liquid 83, i.e., the length

5 that is cooled to a superconducting state.

From the disclosure, drawings, and claims, other embodiments of the invention will be apparent to those skilled in the art.

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